

General Relativistic MHD Simulations of Jet Formation

Y. Mizuno*, K.-I. Nishikawa[†], P. Hardee**, S. Koide[‡] and G. J. Fishman*

*NASA/Marshall Space Flight Center, NSSTC, XD12, Huntsville, AL 35805

[†]National Space Science and Technology Center, XD12, Huntsville, AL 35805

**Department of Physics and Astronomy, The University of Alabama, Tuscaloosa, AL 35487

[‡]Department of Engineering, Toyama University, Toyama 930-8555

Abstract.

We have performed 3-dimensional general relativistic magnetohydrodynamic (GRMHD) simulations of jet formation from an accretion disk with/without initial perturbation around a rotating black hole. We input a sinusoidal perturbation ($m = 5$ mode) in the rotation velocity of the accretion disk. The simulation results show the formation of a relativistic jet from the accretion disk. Although the initial perturbation becomes weakened by the coupling among different modes, it survives and triggers lower modes. As a result, complex non-axisymmetric density structure develops in the disk and the jet. Newtonian MHD simulations of jet formation with a non-axisymmetric mode show the growth of the $m = 2$ mode but GRMHD simulations cannot see the clear growth of the $m = 2$ mode.

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INTRODUCTION

Relativistic jets have been observed in active galactic nuclei (AGNs) [1], in microquasars [2] and in GRBs relativistic jets have been inferred from modeling. It is believed that they originate in the region near accreting black holes, and magnetic acceleration is one of the most promising models for jet formation.

Only a few 3D MHD simulations of jet formation have solved the accretion disk self-consistently [3, 4, 5]. These simulations have shown turbulent and complex structures in the accretion disks caused by the non-axisymmetric mode of Magnetorotational instability (MRI). However the influence of non-axisymmetric modes on jet formation has not been studied extensionally. Recently Kigure & Shibata (2005) [6] have performed 3-dimensional non-relativistic MHD simulations of jet formation by the interaction between an accretion disk and a large scale magnetic field including non-axisymmetric modes. They found that the jets have non-axisymmetric structure with $m = 2$ (m is the azimuthal wave number). The non-axisymmetric structure in the jet originates in the accretion disk, not in the jet itself, the Kelvin-Helmholtz instability is ruled out by the stability condition. However, we do not know whether jets formed in GRMHD simulations show the same behavior because the stability and growth rate of the instability is different from the non-relativistic cases. Thus, we investigate the connection between the non-axisymmetric structure in the jet and that in the disk, and we compare the characteristics (e.g. dependence of the jet velocity on the magnetic field strength and black hole spin) of jets found in 3-dimensional non-relativistic MHD simulations by using

NUMERICAL METHOD

In order to study the formation of relativistic jets from an accretion disk- black hole system we use a 3-dimensional general relativistic magnetohydrodynamic (GRMHD) code with Boyer-Lindquist coordinates (r, θ, ϕ) [9, 10, 11].

We consider the following initial conditions for the simulations: a geometrically thin accretion disk rotates around the rotating black hole (spin parameter of a black hole $a = J/M_{BH}c = 0.95$), where the disk density is 100 times higher than the coronal density. The background corona is free-falling into the black hole (Bondi solution). The initial magnetic field is assumed to be uniform and parallel to the rotational axis. In one case we input a sinusoidal perturbation ($m = 5$ mode, 15% of Keplerian velocity) into the rotation of the disk ($\delta v_\phi = 0.15v_K \sin 5\phi$).

The simulation region is $1.0r_s \leq r \leq 60.0r_s$, $0 \leq \theta \leq \pi/2$ and $0 \leq \phi \leq 2\pi$ (i.e. half sphere with mirror symmetry at the equatorial plane) with $150 \times 64 \times 150$ mesh points.

RESULTS

The matter in the disk loses its angular momentum through the magnetic field and falls towards the black hole. A centrifugal barrier decelerates the falling matter and creates a shock at around $r = 2r_s$. The matter near the shock region is accelerated by the $\mathbf{J} \times \mathbf{B}$ force and the gas pressure and forms relativistic outflows. These results are the same as found in previous GRMHD simulations [7, 8, 9, 12]. As a relativistic outflow propagates outward, it shows a waving structure. The outflow structure is almost axisymmetric, even though this simulation runs in three dimensions. In the sinusoidal perturbation case the general properties are almost the same as that of the non-perturbed case (shock and jet formation). However, due to the initial perturbation the disk structure is slightly different from that of non-perturbation case, i.e., there is a thicker and lower density disk near the black hole.

Figure 1 shows a 2D snapshot (x-y plane) of the density in the accretion disk and the magnetic field structure in both cases. In the non-perturbation case the density shows clear symmetric structure. On the other hand, in the sinusoidal perturbation case, the density structure in the accretion disk shows complex non-axisymmetric structure. Part of the non-axisymmetric density structure reflects the initial sinusoidal mode ($m = 5$) and indicates interaction with other (lower?) modes. The initial perturbation in the accretion disk makes some of the matter fall into the black hole immediately and some of the matter rotates around the black hole for a long time. Although the initial perturbation is weakened by the coupling among different modes, it survives and triggers lower modes. As a result, complex non-axisymmetric density structure develops in the disk.

In the jet some non-axisymmetric structure is seen in both cases, but it is very faint. The non-axisymmetric structure in the sinusoidal perturbation case reflects the initial sinusoidal $m = 5$ perturbation to the disk and may mix with lower other modes, (This cannot be seen clearly in Figure 1).